Radio coverage calculations of terrestrial wireless networks using an open-source GRASS system

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Radio Coverage Calculations of Terrestrial Wireless Networks using an Open-Source GRASS System

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Abstract: - Radio network planning and dimensioning have significant impact on the overall system capacity of the cellular communication systems. Various commercial network planning and dimensioning tools with different radio signal propagation models implemented are available on the market. Their price and especially inflexibility led us to look for an open-source solution. The present paper describes usage of the open-source Geographical Resources Analysis Support System (GRASS) for the radio signal coverage calculation. GRASS modules calculating radio coverage prediction for a number of different radio channel models were developed which, together with module considering antenna radiation pattern influence, compute radio signal coverage for a defined cell. The complete network coverage is computed with modules for generating a data base table (e.g. MySQL, PostgreSQL), arranging the values in increasing order and determining maximal received power at each receive location. Additional modules for adapting input data and analyzing simulation results were also developed. The radio coverage tool accuracy was evaluated by comparing with results obtained from a dedicated professional prediction tool as well as with measurement results.

Key-Words: network planning tool, open-source, GRASS GIS, path loss, raster, clutter, radio signal coverage

1 Introduction

Emerging user applications call for increased bandwidth of communication systems. Consequently, higher frequencies are used in wireless systems while the size of radio cells is becoming smaller. The cellular concept enables lower transmission power and frequency reuse in cells that are far enough from each other. However, due to the increased complexity, a wireless system has to be planned carefully. Cellular system planning involves determining the number and the locations of base stations, their hardware and software, frequency and code planning. One of the aims is to efficiently use the allocated frequency band and to assure high radio coverage.

For the calculation of radio coverage, various mathematical radio propagation models are being used [1, 2, 3, 4]. They can be divided into three groups: (i) statistical models, (ii) deterministic (or theoretical) models and (iii) combinatorial models.

Statistical models are described by a mathematical expression depending on the distance between a transmitter and a receiver and numerous parameters. The expression and parameters are obtained by measurements of radio signal in a specific geographical environment. The reliability of the model depends on the accuracy of the measurements and on the resemblance of the environment in which the model is used to the environment in which the measurements were carried out. Due to the simplicity of their mathematical expressions, statistical models enable fast calculation of radio coverage. Typically, they are used to calculate radio coverage of macro-cells.

Deterministic models are based on the physical laws that drive the propagation of radio waves. Examples of considered propagation mechanisms are: free space radio wave propagation, diffraction, scattering, reflection, absorption, and refraction. These models may be used in different environments but require extensive databases of geometrical and electromagnetic environment properties. Deterministic models are complex and computationally demanding. Thus, they are useful only for calculating radio coverage of smaller areas, e.g. micro-cells or inside buildings.

Combinatorial models combine the advantages of statistical and deterministic models, i.e. fast calculation and partial consideration of terrain characteristics. For example, in many commercial tools, statistical models are used as a base and then improved by consideration of shading, diffraction and scattering.

Various commercial programming tools are available for radio coverage calculation. The first representative tools were designed for mobile

Andrej Hrovat, Igor Ozimek, Andrej Vilhar,
Tine Celcer, Iztok Saje, Tomaz Javornik

operators and national regulators, e.g. Planet [5], decibel Planner [5], Vulcano [6] and CS telecom nG [7]. Accordingly, their price was high while their accessibility and spread of usage were low. Later on, some cheaper yet functionally limited tools have appeared on the market, e.g. WinProp [8], RPS [9] and TAP [10]. There are also some custom built technology-specific tools developed by hardware development companies [11]. These tools do not comprise modules for radio network optimization and are intended for specific tasks such as WLAN network planning, calculation of radio coverage inside buildings, design of radio-relay links, etc.

Those mentioned tools do not allow users to add new propagation prediction modules or to adjust the existing ones. From the scientific point of view their usage is therefore very limited. These limitations can be avoided by using an open-source platform which can be upgraded by an arbitrary propagation model. As the terrain relief significantly influences radio wave propagation, a logical choice is to use an open-source geographical information system (GIS). These systems also include built-in functions for displaying results on geographical maps, importing different raster and vector GIS formats, converting geographical coordinates, etc.

Recently, an example GIS-based open-source radio planning tool called Q-Rap has been released [12]. Originally developed by University of Pretoria and the Meraka Institute for the needs of South African Police Services, the software was made publicly available in May 2010. It is designed as a plug-in for the Quantum GIS (QGIS) open source system [13], which is one of the projects of the OSGeo foundation [14]. The propagation prediction model used by Q-Rap is based on free-space loss calculation which is further improved by accounting for knife-edge diffractions and losses due to rounded hills. The Earth curvature is also taken into account. The user's manual for tool operation is available [15], but it does not include detailed descriptions of the structure of the code and the used principles.

For the development of our radio coverage prediction tool, we used Geographical Resources Analysis Support System (GRASS). Similar to QGIS, GRASS is one of the projects of the OSGeo foundation, and has been part of OSGeo since its foundation in 2006. It is one of the most wide-spread open source GIS systems, it has been successfully used for many years and has a wide spectrum of already implemented modules [16]. Compared to QGIS, GRASS has a longer history with roots in the late 70s and early 80s [17]. Nowadays, there is also cooperation between the two systems. For example,

QGIS can be used as a graphical interface to GRASS.

In the paper, the following section presents the GRASS system with its main structure, characteristics and its applicability in the field of radio communications. Next, a description of the radio coverage prediction software developed in GRASS is presented. The essential building blocks for path loss calculation, sectorization, radio coverage calculation, and input/output data conversion and evaluation are explained. In addition, a module for tying various processing modules into a complete radio coverage tool is also described. In section 4, additional GRASS modules for adjusting input data, accuracy evaluation of the new tool and for the simulation results evaluation are described. In the following section the GRASS software package is evaluated by comparing simulation results with field measurements and simulations performed with a professional tool. The execution performances of the developed tool are also investigated. The paper concludes by a description of our experience with the GRASS system and by plans for our future work.

2 GRASS Open Source GIS Tool

GIS systems find their applications in several different fields, including space planning, business management, navigation, environmental protection, demographical data management etc. Several professional GIS tools exist on the market; however, due to their limitations such as price, long response to required changes and limited possibility of tool modifications, the open-source approach to the programming part of GIS technology has also been developed. Similarly to other technologies, GIS technology also benefits from the open-source approach. Some of the advantages are: continuous improvement and control carried out by developers from all over the world, heterogeneous approach to development, accessibility and adjustability.

GRASS is known as one of the most important open source GIS tools. It operates over raster and vector data and includes methods for image processing and display. It is published under the GPL license, its usage is supported under various operating systems including Mac OS X, Microsoft Windows and Linux.

GRASS comprises over 350 already implemented modules for processing, analysis and visualization of geographical data. The core modules and libraries are written in the C programming language. A well documented API (Application Programming Interface) with a few hundred C functions is available for the developers of new modules. The

documentation is up-to-date and is available online [18]. For large projects, processing may be automated by using scripting languages.
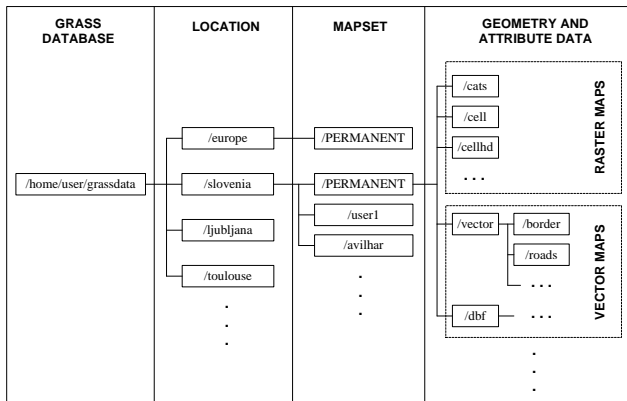

Fig. 1: GRASS data organization

2.1 Structure of Data and Commands

The organization of geographical data in GRASS is depicted in Fig. 1. The data is divided into different locations where each location is defined by its own coordinate system, map projection and geographical boundaries. Each location can have many mapsets where each mapset represents either a subregion or data of a specific user. Users may read and copy data from any mapset while modifications are allowed only within their own mapsets. Such organization enables efficient collaboration between users in a working group. The described structure of maps and files is maintained automatically by GRASS.

Modules for data processing are classified according to their functionality. They are invoked by commands of a form *x.name* where *x* stands for a class and *name* stands for a specific task within this class. Some class examples are:

- g. (general commands),
- r. (raster data processing),
- v. (vector data processing),
- d. (commands for graphical display).

2.2 Usage in the Field of Radio Communications

In its original form, GRASS can be used to analyze a radio coverage that has been either measured or calculated beforehand by using an arbitrary tool [19]. Of course, the data has to be imported into the GRASS environment in a proper form. Alternatively, radio coverage models can be implemented inside GRASS due to its open-source nature. By doing so, potential inconveniences and/or errors that may arise from data format conversion are avoided. The whole process can remain modular as different modules are used for the data analysis and the propagation prediction.

3 Radio Coverage Project in GRASS

We have developed a modular radio coverage tool characterized by a high level of flexibility and adaptability firstly introduced in [20]. It performs separate calculation of the radio signal path loss using an arbitrary channel model, and the inclusion
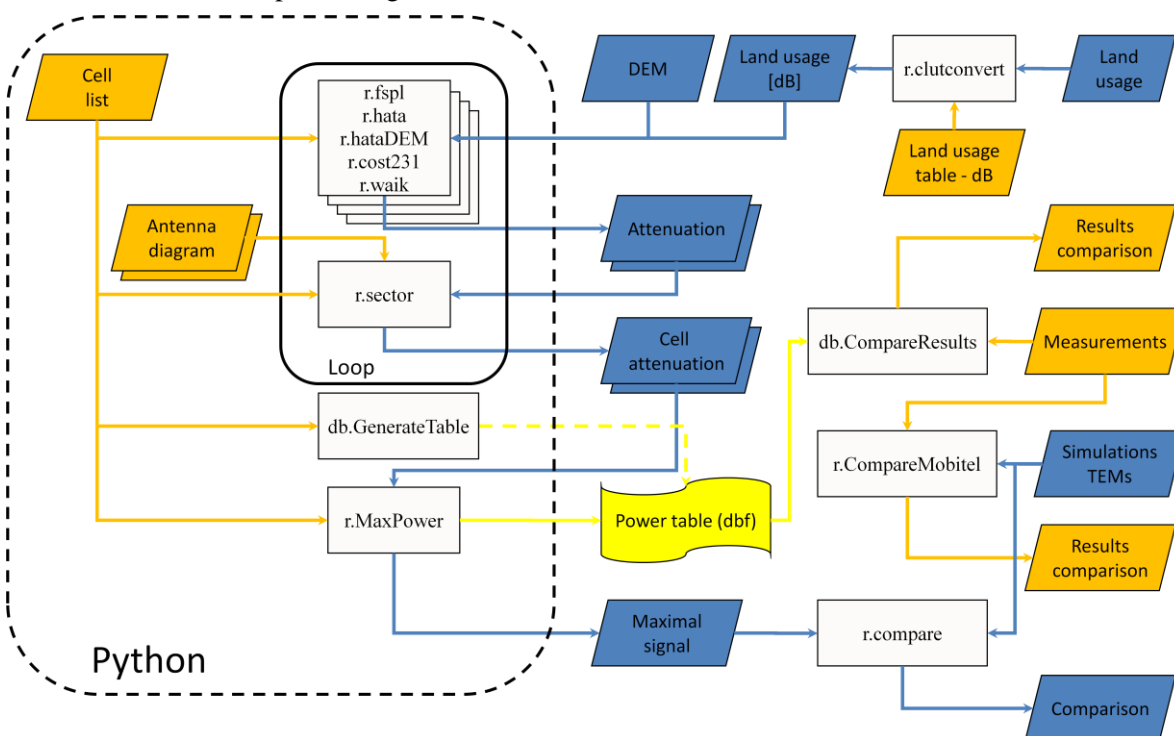

Fig. 2: Radio coverage prediction software block diagram

of antenna radiation patterns and setup parameters such as antenna tilting, azimuth and antenna height. Furthermore, it performs computation of the maximum signal level at the receiver and additional processing of the output data.

The software packet block diagram is presented in Fig. 2. It is composed of two basic compositions of modules. The first part is composed of GRASS modules for radio coverage calculations, which are linked together with a script written in the Python programming language. Additional modules for data comparison and for adapting input data to the GRASS data structure build the second group of GRASS modules.

Besides the GRASS modules represented in Fig. 2 as white squares, the input and output data are also depicted as different colorized parallelograms. Textual input and output files are indicated in orange, GRASS raster files in blue, while databases are denoted in yellow.

The core of the radio coverage software is radio coverage calculation in Fig. 2 encircled with a dashed line. Radio coverage calculation for the whole cellular network is divided into three steps:

- path loss calculation for isotropic source,
- calculation of influence of the antenna diagram, antenna tilt and azimuth,
- storage of N highest calculated received signal strength values into a database.

In the GRASS programming environment every segment is implemented as a separate module. A script written in the Python programming language is responsible for a correct sequence of modules execution. Therefore, each individual module represents a realization of radio calculations only, while the script takes care for the input and output data management. The achieved modularity has several benefits:

- simple upgrade or substitution of existing mathematical modules with new models,
- module independency from a specific network,
- quick and simple recalculation for an individual segment or chosen geographical region,
- possibility of parallelized calculation.

In each step, realization of different modules with the same or a similar task is feasible. Proper module selection is performed through the script and depends on the usage purpose. This is significant especially for the first segment where different mathematical models for radio signal propagation can be taken into consideration. In the first segment, five modules are implemented, *r.fspl, r.hata,*

r.hataDEM, r.cost231 and *r.waik*. The *r.sector* module is currently the only module in the second segment while the third segment contains two modules - *db.GenerateTable* (creates an empty data table for the results) and *r.MaxPower* (arranges the computed data and writes it to the output file).

3.1 Implemented Path Loss Models

Currently, four basic path loss prediction models for the open rural and suburban environments are implemented.

The FSPL (Free Space Path Loss) model implemented in the *r.fspl* module calculates radio signal propagation attenuation in free space with no nearby obstacles to cause reflections or diffractions [21]. At higher carrier frequencies and in environments without many reflections, the *r.fspl* module can serve as the first approximation of the radio signal propagation prediction for the geographical points that are in the transmitter's line-of-sight. Therefore, the calculation must be done in two steps. In the first step, the visibility between the transmitter and each receive point in the area must be determined with the already integrated *r.los* module. Afterwards, the path loss at the LOS points is calculated using the *r.fspl* module.

The *r.hata* module implements the Okumura-Hata model [1]. The model is founded on empirically determined radio propagation characteristics and includes three variants: for the urban, suburban and open environments. The model does not consider terrain configuration neither the environment where the mobile terminal is located, which are its main drawbacks. Radio signal attenuation depends only on the distance, antennas heights and carrier frequencies. To improve the model accuracy, an additional knife edge diffraction module must be implemented.

The COST231 model, realized in the *r.cost231* module, is an extension of the Okumura-Hata model for higher frequencies [22]. It is suitable for medium and large cities where the base station antenna height is above the surrounding buildings. The terrain configuration is only partly taken into consideration. Therefore, the signal is predicted also behind larger geographical obstacles, which significantly contributes to the model inaccuracy.

In the *r.hataDEM* module, a modification of the Okumura-Hata model is implemented [23]. In addition to the carrier frequency, the distance between the transmitter and the receiver, and the receiver and transmitter antenna heights, the model takes into consideration the terrain profile, clutter data and the spherical earth impact. This is the most

Andrej Hrovat, Igor Ozimek, Andrej Vilhar,
Tine Celcer, Iztok Saje, Tomaz Javornik

accurate and sophisticated model implemented in GRASS so far.

Module *r.waik* represents implementation of the Walfisch-Ikegami model [22]. It is a combinatorial model for path loss calculation in urban environment. The model is based on Walfisch-Bertoni [24] and Ikegami model [25]. It distinguishes between LOS and NLOS situations. The terrain profile data are used only for LOS determination. Besides carrier frequency, receiver and transmitter height and distance between them, the model needs additional data about urban environment, namely:

- heights of buildings,
- widths of roads,
- building separation and
- road orientation with respect to the direct radio path.

When the transmitter antenna is above the rooftop the model predicts path loss rather well. The model is relatively useless when the transmitter antenna is bellow roofs because the waveguide effect in street canyons of big cities is not taken into account.

3.2 Antenna Radiation Diagram Influence

After the path loss calculation of the isotropic source for a specific region, the antenna's radiation diagram is considered. Based on the input raster containing the path loss data for the isotropic source, and the antenna's radiation diagram (beam direction, electrical and mechanical tilt, antenna gain) the *r.sector* module calculates the actual path loss for the analyzed cell and writes the data to the output raster for further processing. The example is depicted in Fig. 3.

3.3 Arranging Cells According to Received Power and Writing in Database

After the path loss for each individual cell located within the analyzed area has been calculated, the generated rasters (output rasters form the module *r.sector*) are used for the network radio signal coverage prediction. At each point of the analyzed area the *r.MaxPower* module calculates the received signal strength for each base station based on the base station transmit power and calculated path loss for that base station. The obtained values for

different transmit antennas at each receive location are then arranged in a decreasing order, and the first *n_cell* values are written to the database table previously generated with the *db.GenerateTable* module. The parameter *n_cell* can be arbitrarily chosen in each simulation. The generated database contains the following attributes; x and y coordinates of each location, the raster resolution and receive power level at the location, and the names of the cell and the used path loss prediction model for each of the *n_cell* input values (Table 1). Several database drivers are supported, namely DBF (the default GRASS database driver with very limited capabilities), MySQL and PostgreSQL.
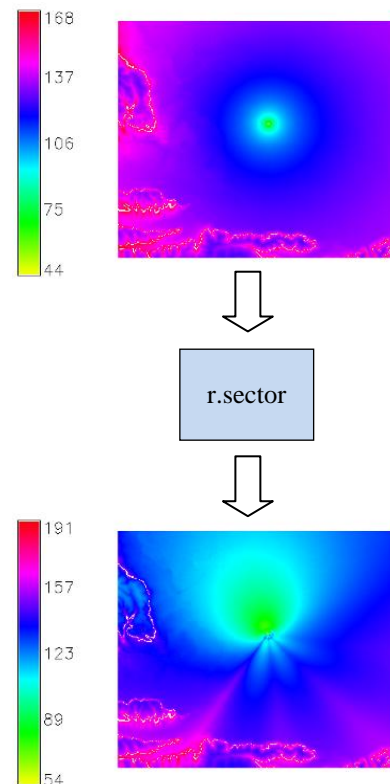

Fig. 3: Input and output raster of *r.sector* module

Furthermore, the module also calculates the parameter E_c/N_0 for the strongest signal for each point of the analyzed area. This parameter describes the ratio between the chip energy and noise power spectral density (including the interference from other users) at the receiver in decibels. It is of

attribute	x	y	resolution	cell1	Pr1	model1	…	cellN	PrN	modelN
format	INT	INT	INT	STR	INT	STR		STR	INT	STR
example	590000	163000	25	SLJUTKA	-8025	Hata_suburban	…	SBANOVB	-10536	Hata_suburban

Table 1: Database structure with the example of the calculated values

significant importance in systems using CDMA such as UMTS as it gives a clear picture of the interference level. The *r.MaxPower* module calculates E_c/N_0 as the ratio between the strongest signal and the sum of signals from all cells included in the simulation.

Finally, the *r.MaxPower* module also generates an output raster file with the maximal received signal strength for each individual point, which can be graphically presented in GRASS GUI (Fig. 4).
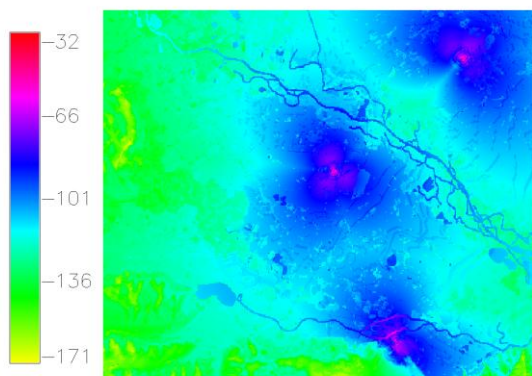

Fig. 4: Radio coverage calculation for flat terrain at 2040 MHz with *r.hataDEM* module

Sometimes we are only interested in the strongest signal values and since the database writing may consume (depending on the number of transmit antennas) the major portion of the module's processing time, this feature is optional (the decision is given through the use of a flag in a module call). In this case the module only generates the output raster file with the maximal received signal strengths which significantly decreases the computation time.

3.4 Python Script

Python [25] is a broadly used and publicly available multiplatform general-purpose high-level programming language. It is an interpreted language, which means that it is simple to use (fast application development and easy modifications - no compilation required), but less effective for computationally intensive tasks. With its automatic compilation into a more effective intermediate bytecode and with today fast processors, even the limited execution speed is not such a problem. It is ideally suited for creating low and medium speed applications such as user interfaces or other general tasks, calling modules written in other languages (such as C) to perform computationally demanding functions. Many software applications, including GRASS, support use of interpretive languages such as Python for adding user-defined functionality.

While our modules for numerically intensive computations of radio signal coverage are programmed in C, we chose the Python programming language for the user interface and to tie everything together. Creating user interface itself was much simplified by the fact that GRASS has built-in support for this, offering input parameter parsing and checking against allowed values, and also automatically generating graphic user interface at run time if a user wants to use it (Fig. 5). The necessary information about the input parameters for this task is given in a form of special pseudo comments as part of the Python code.

Our Python script, *r.radcov*, first reads an input table in the CSV (Comma-Separated Values) format, which specifies configuration of the radio cells comprising the radio network (Table 2). The input table gives positions and orientations of antennas for each location, with antenna types, transmission powers and radio propagation models used. The script also takes a number of parameters (as command-line arguments or via the GRASS's auto-generated GUI) that specify global simulation data such as radio transmission frequency, underlying geographic DEM (Digital Elevation Map), input and output file names etc. The script performs extensive checking of these parameters as well as the contents of the input table against valid values, and reports any errors.

Fig. 5: *r.radcov* GRASS GUI interface

Next, *r.radcov* performs coverage computation by fist calling modules for selected propagation models (e.g. *r.hata*, *r.cost231*) for all transmission locations and then applying antenna transmission beam

forming taking into account antennas' radiation diagrams and their orientations (module *r.sector*). These two computation steps result in a number of files, each containing coverage data of an antenna on a particular transmission location. Since these calculations can be rather time consuming due to the possibly large number of transmit antennas (e.g. more than thousand), the computations are done selectively only for those locations/antennas that have not been calculated yet in a previous run.

userLabel	SLJUTKA	SLJUTKB	...
beamDirection	120	310	...
electricalTiltAngle	1	1	...
mechanicalAntennaTilt	0	0	...
heightAGL	22	22	...
antennaType	742265	742265	...
positionEast	592182	592182	...
positionNorth	153422	153422	...
power	27,5	27,5	...
radius	10	10	...
model	hata	hata	...
P1	suburban	suburban	...
P2	-	-	...
P3	-	-	...
P4	-	-	...

Table 2: Example of radio cells data

Finally, *r.radcov* calls the *r.MaxPower* module to join all partial coverage results for individual transmit antennas into a complete coverage data, producing a raster map file and (optionally) a database table for further processing. For creating the database the user can choose between various database applications such as MySQL [26] or PostgreSQL [27] in addition to the GRASS' internal DBF file support.

4 Modules for Data Analysis and Input Data Adaptation

Radio coverage prediction software is supplemented with some additional GRASS modules required for input data adjusting, accuracy evaluation of the radio

coverage tool and for the simulation results evaluation.

Module *r.clutconvert* is used to convert an input clutter file to the appropriate format with correct attenuation values, while modules *r.compare*, *db.CompareResults* and *r.CompareMobitel* have been developed for verification and analysis of simulation results.

4.1 Convert Clutter Data
Module *r.clutconvert* converts an original clutter file, which includes land usage codes, into a new file with proper predefined attenuation values for a particular terrain type. The module reads an input land usage raster file, and a textual file with the frequency depended attenuation values written in the correct sequence. The resulting output raster file with corresponding attenuation factors for each particular terrain type is then used as the input of the chosen path loss model.

4.2 Simulation Results Comparison
Module *r.compare* serves for calibration and verification of the designed radio coverage prediction tool. It compares simulation results obtained from the GRASS radio coverage prediction tool with those produced by the TEMS software package. The inputs are two raster files containing information about signal strengths and path loss for a particular area. The module calculates the difference in signal strengths at the given receive points and generates an output database table and a raster file, which can be shown also in GRASS GUI.

4.3 Measurements and Simulations Comparison
We have also developed two modules for the evaluation of the accuracy of the designed radio coverage prediction tool with respect to the actually measured results. The first module, *db.CompareResults*, compares the calculated values with the values obtained during a field measurement campaign. The module reads each row of the text file

attribute	time	x	y	cell	rscp	x_rast	y_rast	rscp_sim	model	rscp_diff
example	2005-10-05 10:54:00	592000	153790	SLJUTKB	89.1200	592000	153800	-95.4000	Hata_suburban	6.28

Table 3: Attributes in output textual file of *db.CompareResults*

Andrej Hrovat, Igor Ozimek, Andrej Vilhar,
Tine Celcer, Iztok Saje, Tomaz Javornik

with field measurement data and saves the x and y coordinates, the measured signal level and the name of the cell. The module first maps the coordinates to the nearest coordinates in the database (as they do not necessarily coincide), finds the corresponding row in the database and then extracts the received signal level for the required cell. The data for the measured and calculated signal level, their difference in decibels along with the location, the used path loss prediction model and the cell name are finally written to the output text file (Table 3).

The second module, *r.EvaluateSimulations*, compares the field measurements and the strongest simulation signal levels, neglecting the information about the serving cell. The module output is a textual file including the same fields as the output of the *db.CompareResults* module. The module enables comparison of field measurements with simulation results calculated with the designed radio coverage prediction tool or the commercial tool TEMS.

Because of different input raster files (a GRASS raster file includes values for maximal received power while a TEMS raster file contains path loss values) additional selection is done with the *"GRASS MaxPower raster"*. In the case of the TEMS input raster file, an average transmitted power value must be entered for the receive power calculation.

5 Radio Coverage Tool Performance Analysis

The performance and accuracy of the developed modules for radio signal coverage prediction was investigated by comparing simulation results and field measurements. The reference values were obtained by comparing field measurements with simulation results acquired from the professional radio signal coverage prediction program TEMS. In both simulation tools we used the modification of the Okumura-Hata propagation model [23].

Received power

Difference between calculated and measured received power

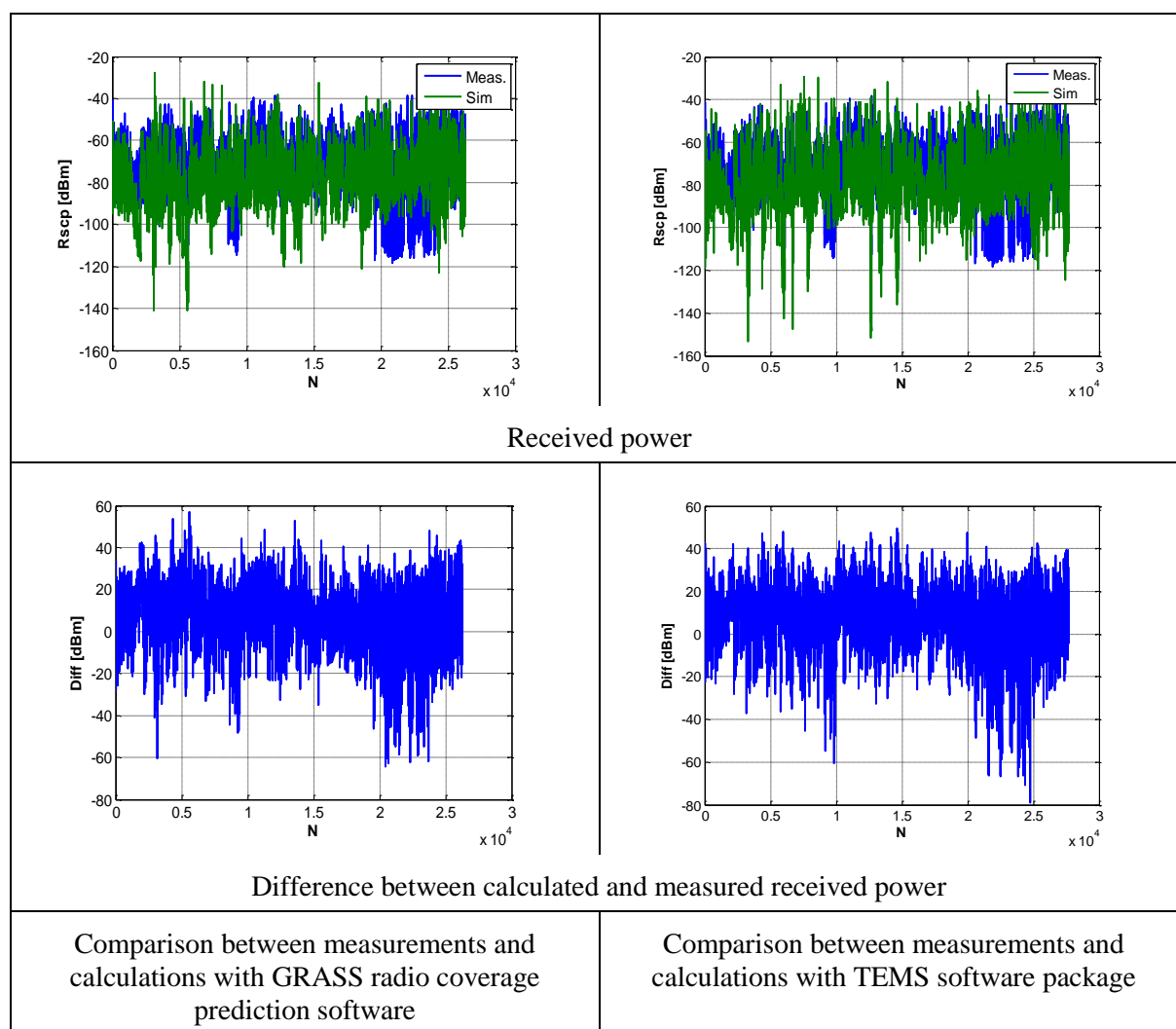| Comparison between measurements and calculations with GRASS radio coverage prediction software	Comparison between measurements and calculations with TEMS software package

Fig. 6: Comparison simulations and measurement results at 2040MHz for suburban environment

The performance of the new software package was investigated for different types of networks (GSM, UMTS) and terrains (hilly and almost flat rural, urban, and suburban). The evaluation of the developed software for different frequency bands is presented first, followed by an analysis for a different terrain type.

The accuracy of the GRASS prediction software can be verified from the charts on Fig. 6, 7 and 8. On the left side, the charts comparing the measurements and calculations with the GRASS radio coverage prediction software are depicted, while graphs showing the comparison between the measurements and calculations with the TEMS software package are on the right.

Fig. 6 and 7 are presenting the simulation results from both tools and the field measurements in suburban environment for 900MHz and 2040MHz. Received power charts clearly shows that the simulation results match the measured values rather

well. Slightly better agreement can be perceived in the 900MHz frequency band (Fig. 7). The deviation among the measurements and simulations for both software applications is depicted in the second raw of diagrams in Fig. 6 and 7. It is evident that the difference between the diagrams on the left- and on the right-hand side for both frequencies is minor. Thus, it can be concluded that the results from the developed radio coverage tool are comparable with the results from the TEMS application and are independent from the used frequency band.

Additional analyses were done on different terrain types. The analyses for the flat rural environment are depicted in Fig. 8. The curves on the charts showing the difference between the measurements and simulations for both software applications have similar course. This confirms applicability of the developed software also for arbitrary terrain types.

The developed radio coverage software gives similar results as the professional TEMS software
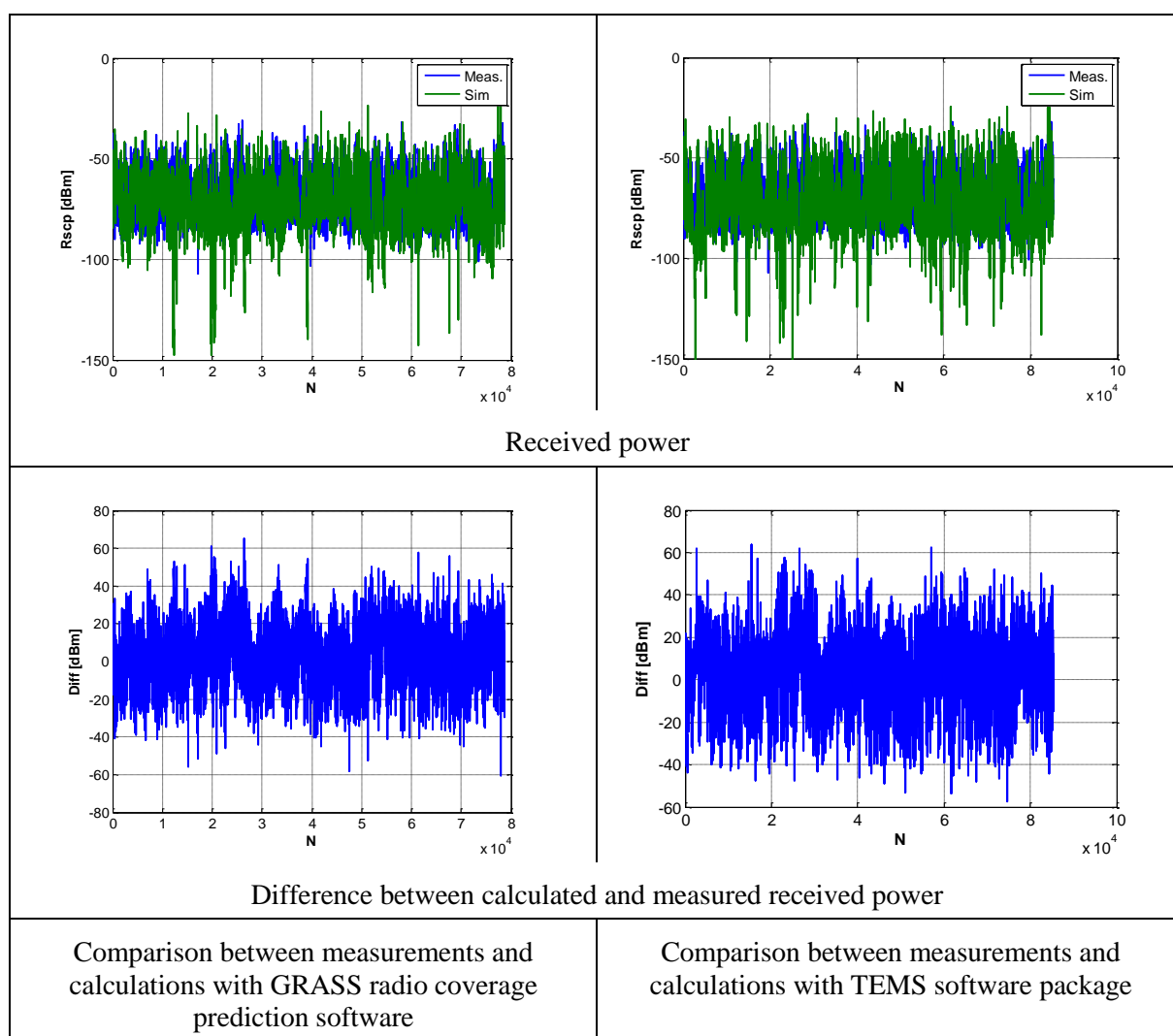

	Received power	
	Difference between calculated and measured received power	
Comparison between measurements and calculations with GRASS radio coverage prediction software		Comparison between measurements and calculations with TEMS software package

Fig. 7: Comparison simulations and measurement results at 900MHz for suburban environment

Andrej Hrovat, Igor Ozimek, Andrej Vilhar,
Tine Celcer, Iztok Saje, Tomaz Javornik

Received power	

Difference between calculated and measured received power	

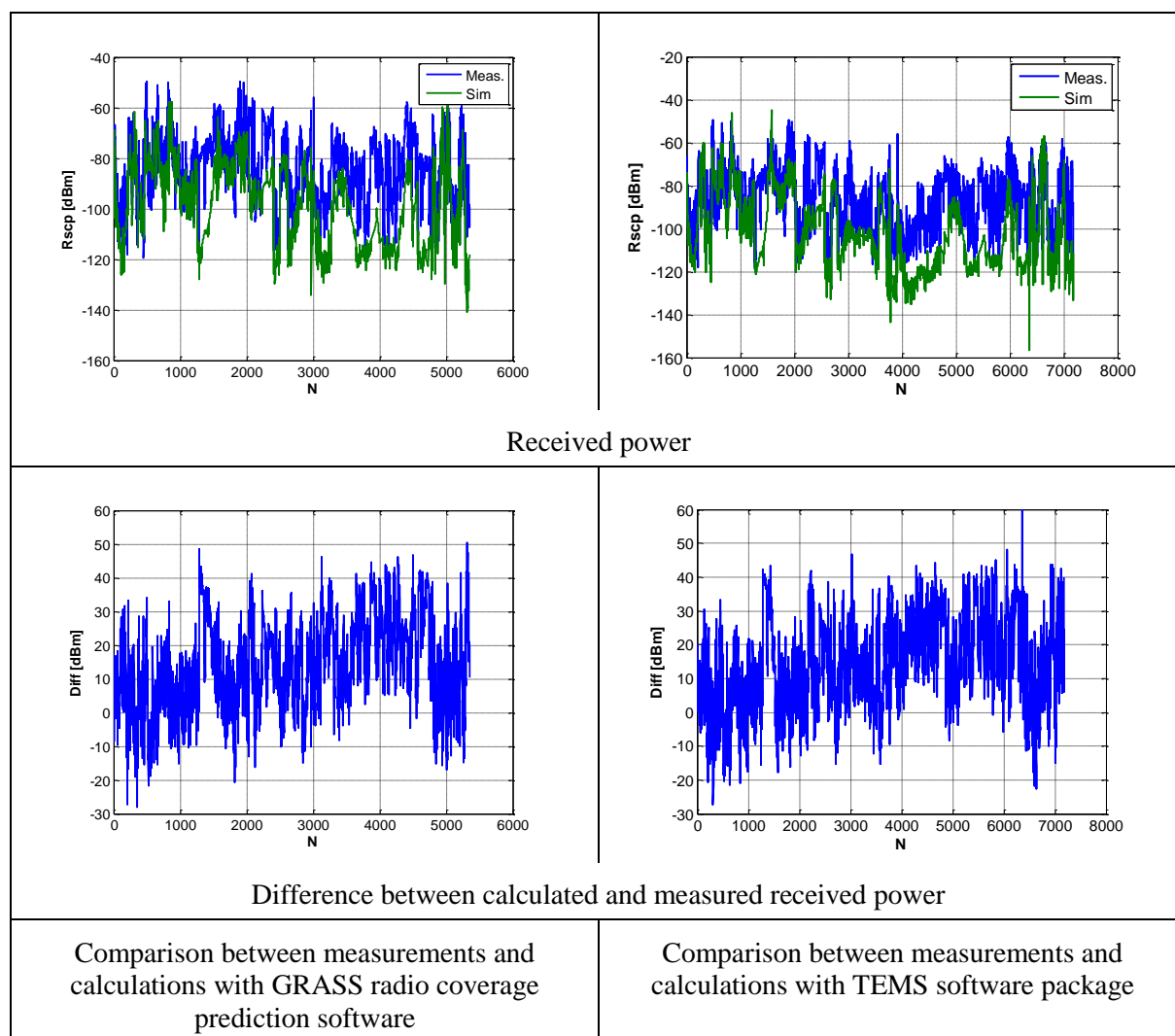| Comparison between measurements and calculations with GRASS radio coverage prediction software	Comparison between measurements and calculations with TEMS software package

Fig. 8: Comparison simulations and measurement results at 2040MHz for flat rural environment

irrespective of the operational frequency or chosen terrain type. The computed values are comparable also for different distances between the base station and the receiver. Some negligible differences between the results originate from the fact that the implemented path loss model in the TEMS software used in the simulation is not entirely available and thus cannot be realized in the GRASS software in a completely identical way.

Additionally, execution performance of the developed modules was evaluated in terms of the required processing times on our system (processor Intel Core2 Quad CPU 2,66GHz, disk WD2500KS, OS Linux RHEL5). The simulated configuration included eight transmission antennas on four locations (base stations), therefore requiring four model and eight sector computations. Two different geographic regions were used: a small one, "Ljutomer", encompassing all transmission locations (15 x 13km, resolution 25m) and a large one

"Slovenia" (whole Slovenia, 285 x 185km, resolution 100m). The effective transmission radius was limited to 10km. The results for single core execution are given in Table 4. The *hataDEM* model was not simulated for the whole Slovenia region since its clutter map was not available to us. The *r.MaxPower* module was not run with DBF database on the whole Slovenia region since the internal GRASS DBF processing is very memory inefficient, keeping the whole database in the main memory and hence running out of memory for large regions.

	Ljutomer	Slovenia
r.hata	0,35s /model	1,7s/model
r.hataDEM	2,0s/model	-
r.sector	0,35s/model	1,8s/sector
r.MaxPower, GRASS DBF	27s (8 sectors)	-
rMaxPower, MySQL	55s (8 sectors)	16m 38s

Table 4: Execution performance

Andrej Hrovat, Igor Ozimek, Andrej Vilhar,
Tine Celcer, Iztok Saje, Tomaz Javornik

6 Conclusion

Precise and efficient planning of the wireless telecommunication systems requires efficient and exact radio signal coverage calculations. The high price and limited functionalities of the existing professional network planning tools compels to look for alternative solutions. The needs can be fulfilled using an open-source system which gives possibilities to improve the existing models based on measurements, or to develop entirely new path loss prediction models.

This paper presented a radio signal coverage prediction software tool developed for the open-source GRASS system. After a short introduction of the GRASS GIS system, a detailed description of the coverage prediction software was given. The tool enables a high level of flexibility and adaptability. It is composed of several GRASS modules for path loss calculation, a sectorization module, a module for radio signal coverage calculation, and additional modules for preparing input data and analyzing simulation results. Modules can be used individually or through the *r.radcov* module, written in Python, which interconnects individual modules into a complete radio signal propagation software package. At the end, the developed software was evaluated by comparing with the field measurements and simulation results obtained from a professional software application.

The radio signal coverage prediction software implementation was quite straightforward, as API is well developed and documented. The set of built-in C functions is adequate. The possibility to study parts of the already implemented code is also very helpful.

Extensive performance analyses showed satisfactory results. Compared to a professional network planning tool, the computation speed is slightly lower while the result accuracy is completely comparable irrespective of the terrain type or operational frequency. For better agreement between simulations and measurements, additional model tuning will be performed. In our future work, we also plan to expand the functionalities of the developed software package and build additional path loss modules for the urban and hilly rural environments that will also include the elements of ray tracing techniques and additional environment data [29].

The achievement made so far represents a strong base for future work and is interesting both from the point of view of researchers as well as network developers. The whole source code of the radio signal coverage prediction tool together with detailed instructions will be publicly available at http://commsys.ijs.si/en/software/grassradiocoverage tool. The tool can be freely used, modified and upgraded with new path loss modules.

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